MODELING OF THE NON-AUDITORY RESPONSE TO BLAST OVERPRESSURE

Rupture Strength of the Rabbit Large Intestine

ANNUAL/FINAL REPORT

James H.-Y. Yu
Edward J. Vasel

JANUARY 1990

Supported by

U.S. ARMY MEDICAL RESEARCH AND DEVELOPMENT COMMAND
Fort Detrick, Frederick, Maryland 21701-5012

Contract No. DAMD17-85-C-5238

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FOREWORD

In conducting the research described herein, the investigator(s) have adhered to the "Guide for the Care and Use of Laboratory Animals," prepared by the Committee on Care and Use of Laboratory Animals of the Institute of Laboratory Animal Resources, National Research Council [DHEW Publication No. (NIH)l 78-23, Revised 1978].

19. ABSTRACT *(Continued from front)*

RUPTURE STRENGTH OF THE RABBIT LARGE INTESTINE

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ABSTRACT

In support of the study of blast overpressure related G.I. injury, an extensive set of in vivo tests were carried out to determine the rupture strength of the large intestine for the New Zealand White rabbit. In all, 21 rabbits with various weights for both sexes were tested. Results of the tests indicate that physical dimensions and rupture strengths are not dependent on sex or weight of adult rabbits but instead correlate with position along the G.I. tract. The ascending colon has the highest rupture pressure followed by caecum, transverse colon, and descending colon. The rupture strength in terms of unit thickness, however, decreases systematically along the G.I. tract from caecum to descending colon. The results agree with the set of data given by Yamada and obtained from pre-processed, in vitro test samples.

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1. INTRODUCTION

Previous studies have shown that strong or repeated blast overpressure (BOP) could result in injury to the gastrointestinal tract. Such injury ranges from simple surface contusions to severe hemorrhage and intestinal wall rupture. Field tests have shown that the single BOP trauma threshold for G.I. tract injury appears to lie between that of the larynx and the lung and may be a critical element in defining Damage Risk Criteria (DRC) for combat exposure.

When an animal is exposed to blast overpressure the events leading to G.I. injury follow the general sequence shown in Figure 1. The free field blast produces body loading which produces body distortion. Body motion results in a local deformation of air-containing organs. When the organ deformation exceeds the limit of tissue strain, contusive capillary injury occurs. Determining the critical stress corresponding to the limiting strain is central to prediction of blast injury and the establishment of a DRC.

Fundamental to prediction of G.I. blast injury is the determination of the basic parameters and organ physiological properties which affect the G. I. injury mechanism. Higher static intestinal material strength could be indicative of higher resistance to blast injury and vice versa. Rupture strength tests, therefore, offer a simple and direct means of establishing a reference material strength data base for each G.I. section type.

To understand the loading-injury relationship, an in vivo procedure was established to determine the rupture strengths for each part of the large intestine for the New Zealand White rabbit. This data was taken for adult rabbits of both sexes and various weights, and compared with results from a previous test using in vitro G.I. samples.

Explosion

↓

Waves

↓

Body Loading

↓

Organ Distortion

↓

Tissue Strain

↓

Injury

Figure 1. Common mechanical sequence of injury.

2. INSTRUMENTATION

The three major quantities measured in the rupture strength tests were the intestine diameter, wall thickness, and the internal pressure.

2.1 Internal Pressure Measurement

An aluminum reservoir, Figure 2, with Plexiglas end plates was fabricated to facilitate the tests. The transparent end plates allowed ready monitoring of reservoir fluid level, and the refill cock allowed for easy refill and pressure relief. A sphygmomanometer hand pump and its pressure gauge were used to pressurize the test sections.

2.2 Wall Thickness Measurement

A NOVA 201A ultrasonic thickness gauge, Figure 3, was used to measure the thickness of the intestine wall. This instrument uses the traveling time of ultrasonic frequency pulses between transmitted and interface-echoed signals to measure the material thickness. Using the D2 sensor, which has a 12 MHz frequency, a resolution of 0.0025 mm can be achieved. A small injected air bubble positioned directly underneath the point of measurement provided the tissue-gas interface.

Since the wave propagation speed in the intestine tissue was not known, a priori, the absolute value of the tissue thickness needed to be calibrated. This was done by carefully measuring a soft tissue sample with a micrometer. The average value of many repeated measurements was then set on the readout by the gain adjustment dial to be the ultrasonic reading for the tissue measured with the D2 sensor. This gain setting was then used for all subsequent tests.

To facilitate subsequent recalibration, the exact reading of a piece of metal plate using the tissue gain setting was noted. For all subsequent tests the reading of the reference metal plate was checked and the dial reset if necessary. It was found that the instrument had very little drift with time.

2.3 Diameter Measurement

Previously, a vernier caliper was used to measure the diameter of the pressurized intestine. The average value in the mesentery plane and that perpendicular to it was taken as the mean diameter. This was a fair representation when the intestine had a roughly circular cross section. However, for an irregular shaped section, such as the ascending colon, this approach could give a biased result.

To improve the accuracy of measurement and provide a better representation of the mean diameter for all intestine parts, circumference measurement was used. A flexible tape was used to measure the perimeter of the chosen cross section. The equivalent diameter was then calculated. The tape measure had a resolution of 0.05 cm; giving an equivalent resolution of 0.015 cm for the diameter measurement.

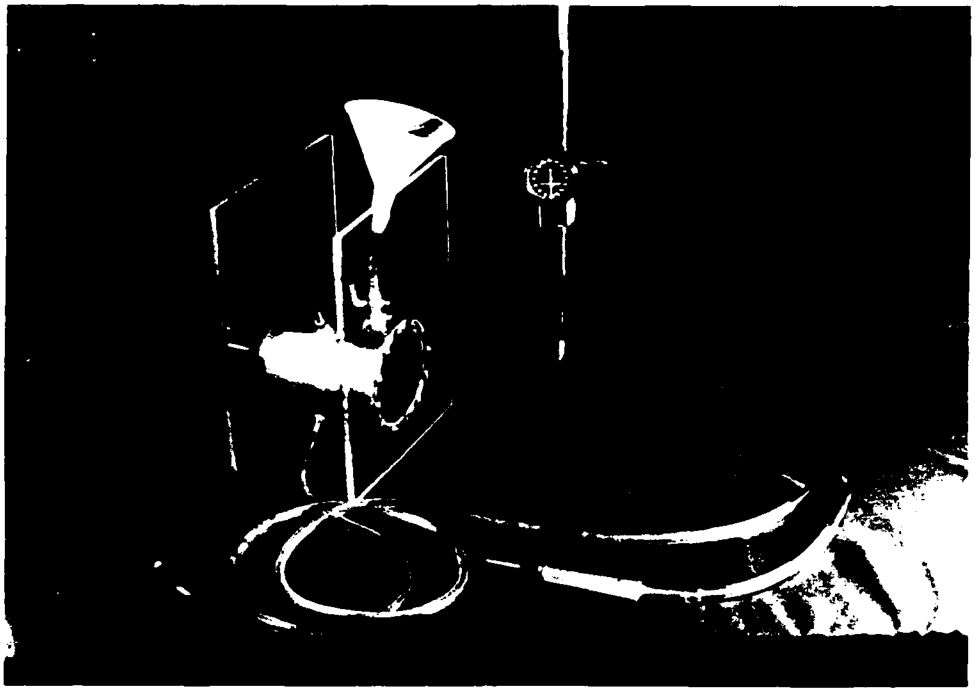

Figure 2. GI tract burst strength test setup.

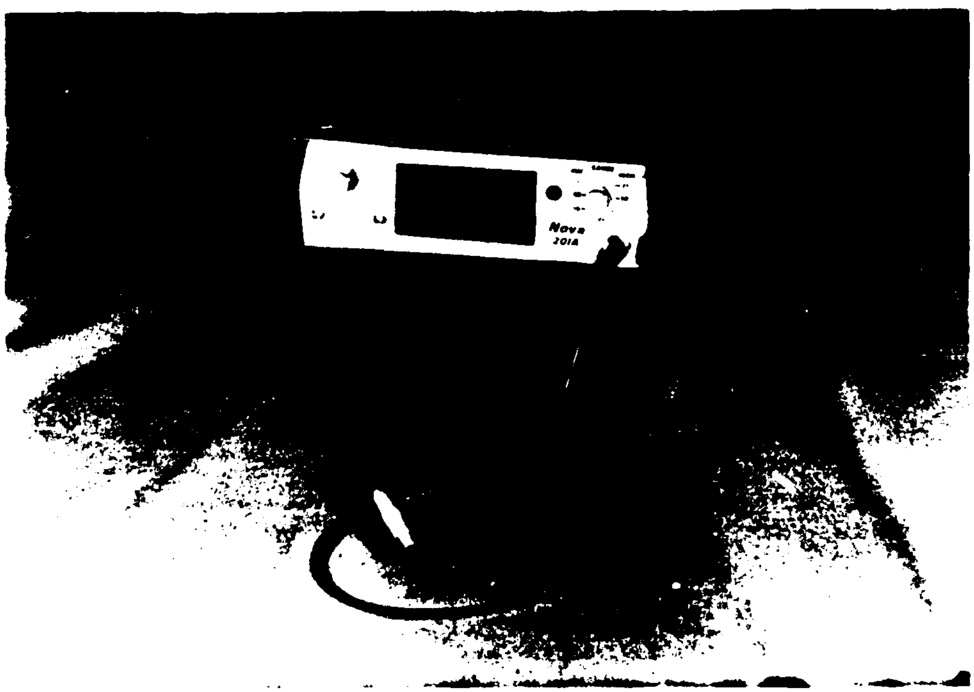

Figure 3. NOVA 201A digital ultrasonic thickness gauge.

3. DATA COLLECTION AND REDUCTION

3.1 Test Specimen Preparation and Data Taking Scheme

Each rabbit was prepared following this standard procedure. The rabbit was anesthetized by administering ketamine (50 mg/kg) I.M. followed by I.M. injection of a combination of xylazine (5 mg/kg) and acepromazine (1.25 mg/kg). The anesthetized rabbit was weighed and then restrained in the warm saline operation bath shown in Figure 4. The circulating bath was kept at 37°C. To reduce shock and possible physiological property change due to organ isolation, the rupture tests were carried out in vivo. Dissection of mesenteric tissue and fascia for placement of ligatures was kept to a minimum to keep the circulatory network intact.

The rabbit's large intestine consists of four major intestine parts: descending colon, transverse colon, ascending colon and caecum. Because there is no clear demarcation between the various parts, the following scheme was used to distinguish them. As shown in Figure 5, the first 25 cm or so measured from the rectum was defined as the descending colon; the next section up to the ascending colon was defined as the transverse colon. This was followed by the ascending colon and the caecum. Each intestine part was then divided into two subsections to yield a total of eight test regions for the large intestine. Measurements were taken at two and sometimes three locations for each subsection to test whether there was any variation along the intestine.

In order to check the effect of test section length-to-diameter ratio on bursting strength, samples of 5, 10 and 15 cm specimens were tested. Though no apparent differences were noticed among them, subsequent tests were carried out using an average test section length-to-diameter ratio of 5:1. This minimized the effect of test section length on the circular stress value.

An extensive initial set of tests measured in two mutually perpendicular planes for each test location showed little variation in wall thickness between them. Therefore, to reduce the amount of handling of the test section, subsequent thickness measurements were made at the surface of the test section where the air bubble accumulated during pressurization.

3.2 Test Procedures

After the test section was prepared, one end of it was ligated. A 14 gauge catheter was inserted into the remaining end and secured with a ligature. The pressurizing system shown in Figure 2 was then connected to the catheter. During pressurization the air-water interface in the aluminum reservoir was maintained at the same level as the test section to alleviate hydrostatic effects. Therefore, the gauge reading represented the net pressure in the test section.

A low pressure was then applied to the pressurizing system by the sphygmomanometer hand pump to fill the test section. A small bubble of air was introduced to facilitate wall thickness measurement. Once the test section was full, the bleed cock on the reservoir was opened to establish the zero pressure test condition in the sample. Test section length, circumference and wall thickness were then measured to establish the benchmark conditions. After that, test pressure was gradually increased until burst, pausing at 3.32 kpa (25 mm Hg) pressure intervals for data acquisition.

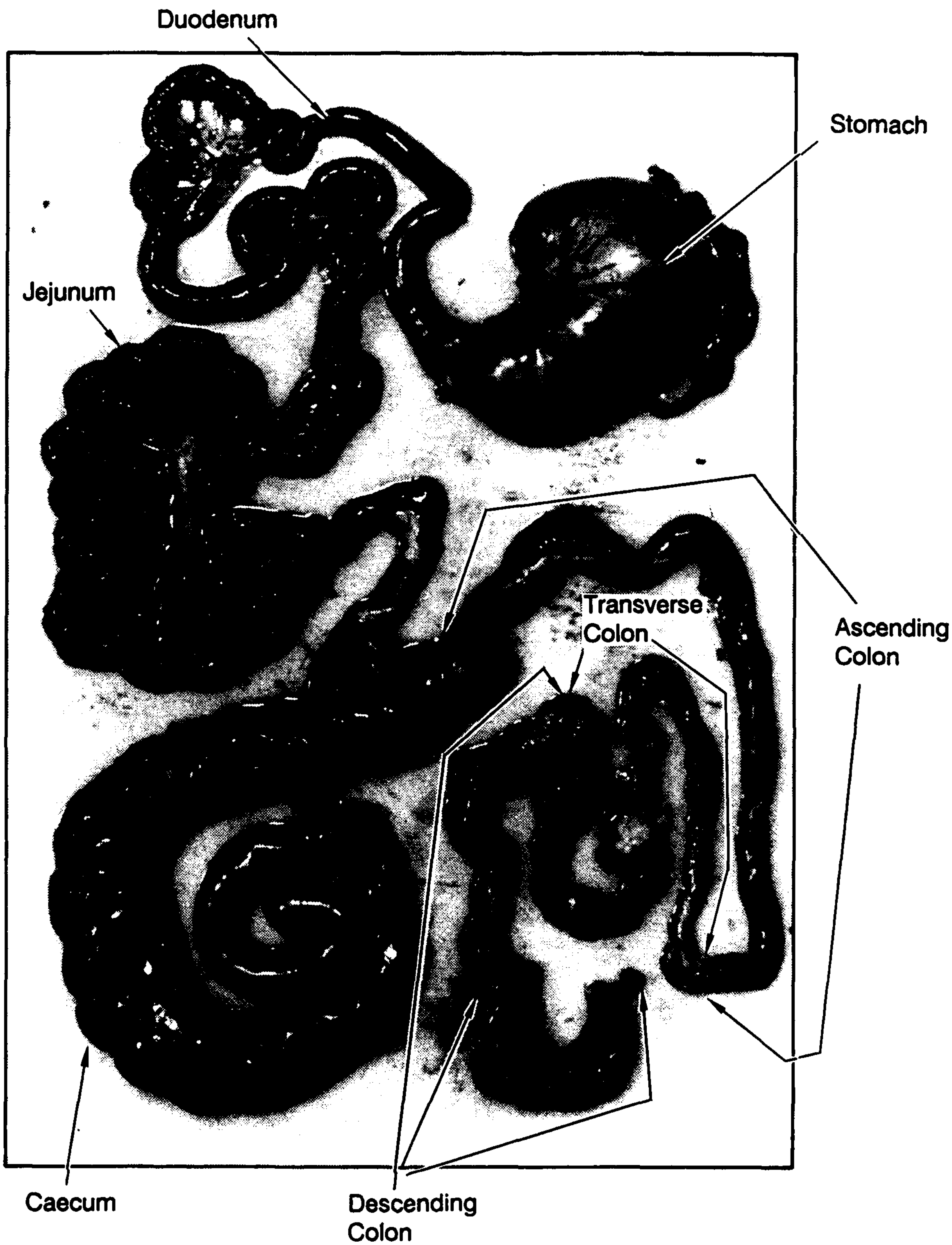

Figure 4. Rabbit G.I. tract test section definition.

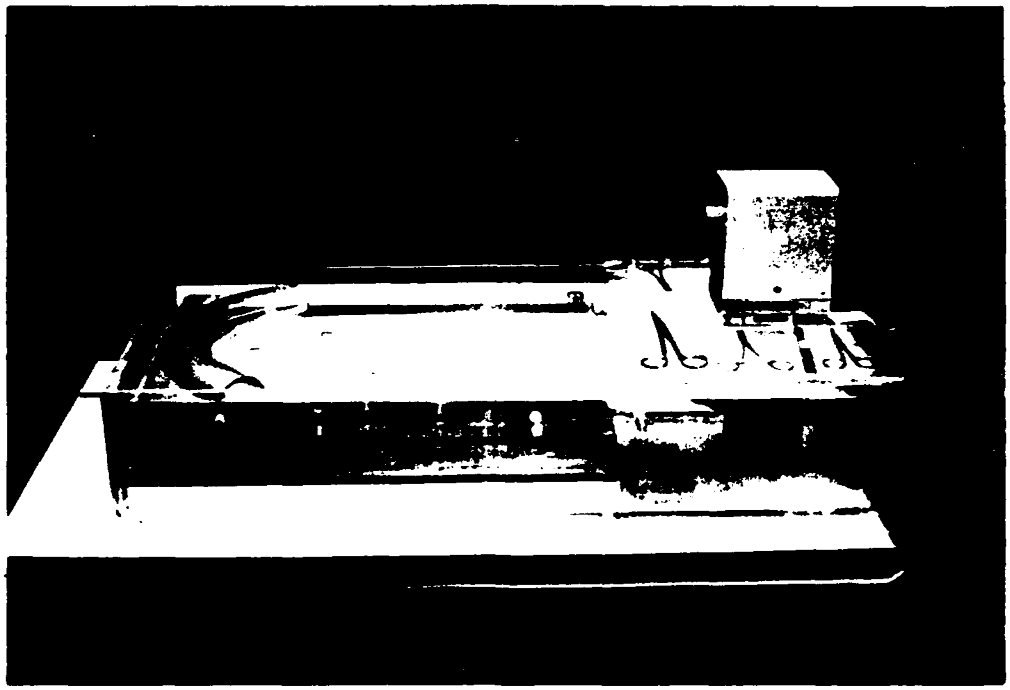

Figure 5. Constant temperature circulating saline bath for GI tract preparation.

For each test subsection, two quarter-length locations from each end along the intestine were chosen for data taking. Three separate readings of circumference and wall thickness were taken at each of these locations.

4. RESULTS AND DISCUSSION

The circular stress, σ, was calculated according to the equation:

$$\sigma = \frac{P_B D_B}{2t_B}$$

where D_B and t_B are, respectively, the diameter and wall thickness at burst, and P_B is the bursting pressure.

Except for the consistently different values between the two subsections of the ascending colon, there were no systematic differences among the data taken at the four locations of each intestine part. Therefore, the average value from the four locations (two for each ascending colon subsection) was taken as the representative mean for each intestine part. The results are summarized in Tables 1 through 4.

As shown, despite the large number of data taken for each rabbit, there was considerable scatter among the rabbits. No clear trend seems to exist in the physical dimension nor the bursting strength for the various weight rabbits with the exception of perhaps the very young and the much older ones, which appear to have relatively low and high bursting values, respectively.

The overall mean and sample standard deviation were calculated over all weights of each intestine part. These results are summarized in Table 5. They could be used to represent the profile and physical properties of the large intestines of adult New Zealand white rabbits. The negligible difference between male and female rabbits further illustrates that for a test rabbit in an adult weight range, age and sex, play no significant role in their rupture strength nor physical dimensions.

One special feature does stand out from this series of tests, i.e., the high rupture pressure of the ascending colon. Furthermore, when the diameter and wall thickness are taken into consideration, the circular stress $\sigma = P_B D_B / 2t_B$ decreases systematically from caecum to the descending colon.

Previous work quoted by Yamada (1970)* for rabbits listed the following results:

Caecum	2.13 ± 0.31 kpa
Ascending colon	4.23 ± 0.20 kpa
Rectum	2.28 ± 0.54 kpa

Though no details are given with regard to the species tested, the mean values agree well with our in vivo data. These results were obtained using isolated test specimens, pretreated with saline solution and stored overnight in a refrigerator. It was claimed that such preparation procedures would result in more consistent material strength of the test samples.

Table 1. Rupture Properties of Rabbit Caecum

Sex	Wt (kg)	D_o (cm)	D_B (cm)	t_o (mm)	t_B (mm)	P_B (kPa)
Male	2.58	3.10	3.81	0.351	0.262	9.31
	2.60	3.40	4.06	0.345	0.241	13.17
	3.13	3.25	3.66	0.495	0.345	9.93
	3.29	3.28	3.68	0.404	0.244	18.61
	3.61	3.05	3.78	0.381	0.264	16.62
	3.73	3.58	4.14	0.445	0.330	16.68
	3.77	3.18	3.81	0.490	0.358	17.17
	3.82	3.51	3.71	0.351	0.312	10.00
	4.01	2.97	3.51	0.445	0.343	19.99
	4.07	3.40	3.96	0.396	0.300	13.17
	4.80	3.35	4.01	0.386	0.269	23.92
	5.02	3.12	3.91	0.394	0.277	18.34
	$\bar{x}$	1.29	3.84	0.406	0.295	15.58
	σ_{n-1}	0.075	0.188	0.52	0.41	4.55
Female	2.63	3.15	3.86	0.384	0.297	15.17
	2.81	3.78	4.39	0.274	0.234	10.00
	3.21	3.28	3.94	0.401	0.287	14.55
	3.80	3.23	3.86	0.419	0.320	13.17
	3.85	3.68	4.29	0.345	0.274	10.00
	3.90	3.43	4.22	0.384	0.287	12.55
	4.51	3.33	4.14	0.394	0.267	15.65
	4.71	3.10	4.01	0.371	0.246	14.96
	4.73	3.76	4.55	0.373	0.272	11.65
	$\bar{x}$	3.40	4.14	0.371	0.277	13.10
	σ_{n-1}	0.264	0.244	0.42	0.26	2.21

D_o, t_o: Diameter and thickness of intestine filled with saline at zero gauge pressure

D_B, t_B: Diameter and thickness of intestine before bursting

P_B: Bursting Pressure

Table 2. Bursting Properties of Rabbit Ascending Colon

A. Proximal Ansa of Colon

Sex	Wt (kg)	D_o (cm)	D_B (cm)	t_o (mm)	t_B (mm)	P_B (kPa)
Male	2.58	1.96	2.67	0.790	0.615	18.61
	2.60	2.16	2.90	0.897	0.681	19.99
	3.13	2.29	2.77	0.569	0.340	19.99
	3.29	1.98	2.57	0.556	0.368	29.92
	3.61	2.24	2.62	0.920	0.452	29.92
	3.73	1.27	2.06	0.889	0.635	19.99
	3.77	2.01	2.44	0.612	0.437	23.30
	3.82	1.63	2.13	0.569	0.452	16.62
	4.01	2.06	2.39	0.762	0.483	23.30
	4.07	2.31	2.77	0.831	0.516	25.92
	4.80	1.93	2.77	0.640	0.338	27.92
	5.02	1.68	2.49	0.716	0.478	26.61
	$\bar{x}$	1.96	2.54	0.729	0.483	23.51
	σ_{n-1}	0.30	0.25	0.137	0.113	4.55
Female	2.63	1.80	2.46	0.818	0.493	26.54
	2.81	2.26	2.72	0.683	0.462	19.92
	3.21	1.93	2.64	0.899	0.574	23.10
	3.80	1.91	2.54	0.541	0.422	19.23
	3.85	2.06	2.74	0.666	0.429	22.61
	3.90	1.93	2.90	0.729	0.544	21.92
	4.51	1.98	2.84	0.625	0.401	19.92
	4.71	2.16	2.72	0.737	0.386	22.61
	4.73	2.03	3.15	0.841	0.617	26.82
	$\bar{x}$	2.01	2.74	0.726	0.480	21.79
	σ_{n-1}	0.137	0.20	0.112	0.82	2.28

Table 2. (Cont'd)

B. Distal Ansa of Colon

Sex	Wt (kg)	D_o (cm)	D_B (cm)	t_o (mm)	t_B (mm)	P_B (kPa)
Male	2.58	1.35	2.03	0.551	0.417	19.99
	2.60	1.88	2.16	0.658	0.521	18.61
	3.13	1.12	2.11	0.691	0.544	23.30
	3.29	1.40	1.93	0.490	0.437	26.61
	3.61	1.55	1.96	0.681	0.455	33.30
	3.73	1.12	1.75	0.483	0.356	23.30
	3.77	1.40	1.98	0.689	0.394	26.61
	3.82	1.37	1.91	0.544	0.419	19.99
	4.01	1.27	1.83	0.584	0.381	29.92
	4.07	1.24	2.08	0.826	0.472	26.61
	4.80	1.65	2.03	0.599	0.406	36.19
	5.02	1.19	1.85	0.930	0.503	43.23
	$\bar{x}$	1.37	1.96	0.643	0.442	27.30
	σ_{n-1}	0.226	0.119	0.133	0.58	7.31
Female	2.63	1.17	1.88	0.754	0.447	26.54
	2.81	1.47	1.98	0.808	0.386	19.92
	3.21	1.55	1.98	0.653	0.472	23.23
	3.80	1.45	1.91	0.442	0.297	19.92
	3.85	1.52	2.08	0.742	0.427	24.20
	3.90	1.52	2.16	0.488	0.318	21.92
	4.51	1.52	2.08	0.597	0.391	19.92
	4.71	1.52	2.08	0.528	0.363	26.82
	4.73	1.60	2.11	0.516	0.401	26.54
	$\bar{x}$	1.47	2.03	0.615	0.389	23.23
	σ_{n-1}	0.124	0.097	0.648	0.57	2.96

Table 3. Bursting Properties of Rabbit Transverse Colon

Sex	Wt (kg)	D_o (cm)	D_B (cm)	t_o (mm)	t_B (mm)	P_B (kPa)
Male	2.58	1.22	1.91	0.389	0.323	8.48
	2.60	1.42	1.63	0.345	0.264	9.17
	3.13	1.19	1.73	0.511	0.363	10.69
	3.29	1.19	1.52	0.462	0.257	11.65
	3.61	1.47	1.85	0.465	0.406	11.44
	3.73	1.35	1.55	0.394	0.254	10.20
	3.77	1.42	1.88	0.409	0.394	15.51
	3.82	1.12	1.40	0.290	0.252	11.65
	4.01	1.32	1.60	0.394	0.267	11.03
	4.07	1.32	1.83	0.292	0.249	10.00
	4.80	1.30	1.55	0.396	0.297	10.69
	5.02	1.12	1.60	0.3795	0.226	16.62
	$\bar{x}$	1.30	1.68	0.394	0.296	11.43
	σ_{n-1}	0.122	0.165	0.66	0.61	2.38
Female	2.63	1.27	1.70	0.584	0.427	10.27
	2.81	1.42	1.83	0.384	0.318	10.00
	3.21	1.32	1.80	0.396	0.282	11.44
	3.80	1.42	1.85	0.480	0.252	9.51
	3.85	1.52	2.06	0.531	0.340	11.93
	3.90	1.47	1.91	0.414	0.310	9.93
	4.51	1.50	2.11	0.490	0.351	10.00
	4.71	1.47	1.91	0.528	0.379	12.89
	4.73	1.24	1.93	0.660	0.366	14.00
	$\bar{x}$	1.40	1.91	0.496	0.336	11.10
	σ_{n-1}	0.102	0.122	0.91	0.53	1.56

Table 4. Bursting Properties of Rabbit Descending Colon

Sex	Wt (kg)	D_o (cm)	D_B (cm)	t_o (mm)	t_B (mm)	P_B (kPa)
Male	2.58	1.55	2.13	0.396	0.301	7.31
	2.60	1.24	1.80	0.325	0.208	10.34
	3.13	1.45	1.85	0.429	0.254	12.13
	3.29	1.42	1.70	0.544	0.376	10.00
	3.61	1.47	1.75	0.345	0.266	10.00
	3.73	1.55	1.75	0.495	0.368	8.89
	3.77	1.57	1.98	0.404	0.295	12.27
	3.82	1.09	1.68	0.323	0.229	10.00
	4.01	1.47	1.80	0.495	0.330	8.69
	4.07	1.52	2.26	0.422	0.282	10.69
	4.80	1.30	1.65	0.305	0.246	10.00
	5.02	1.07	1.88	0.381	0.262	14.48
	$\bar{x}$	1.40	1.85	0.406	0.285	10.41
	σ_{n-1}	0.175	0.183	0.76	0.52	1.88
Female	2.63	1.27	1.68	0.488	0.386	9.45
	2.81	1.55	2.11	0.302	0.236	9.79
	3.21	1.42	1.73	0.318	0.239	9.79
	3.80	1.50	2.08	0.389	0.325	7.31
	3.85	1.40	2.13	0.495	0.297	9.65
	3.90	1.47	2.08	0.460	0.292	9.03
	4.51	1.37	2.01	0.445	0.285	9.03
	4.71	1.09	1.78	0.389	0.297	9.65
	4.73	1.50	2.13	0.371	0.302	10.89
	$\bar{x}$	1.40	1.98	0.406	0.295	9.38
	σ_{n-1}	0.142	0.188	0.70	0.45	0.96

Table 5. Summary of Bursting Properties of Rabbit Large Intestine

		Diameter (cm)		Wall Thickness (mm)		Rupture Strength (kPa)	
	Sex	D_o	D_B	t_o	t_B	P_B	σ
Caecum	M	3.28±0.191	3.84±0.188	0.406±0.052	0.295±0.041	15.58±4.55	1,014.11
	F	3.40±0.264	4.14±0.244	0.371±0.042	0.277±0.026	13.10±2.21	979.64
Ascending Colon (Proximal)	M	1.96±0.305	2.54±0.25	0.729±0.137	0.483±0.113	23.51±4.55	618.39
	F	2.01±0.137	2.74±0.20	0.726±0.112	0.480±0.082	21.79±2.28	622.53
Ascending Colon (Distal)	M	1.37±0.226	1.96±0.119	0.643±0.133	0.442±0.058	27.30±7.31	603.91
	F	1.47±0.124	2.03±0.097	0.615±0.131	0.389±0.057	23.23±2.96	607.36
Transverse Colon	M	1.30±0.122	1.68±1.65	0.394±0.066	0.296±0.061	11.44±2.41	324.02
	F	1.40±0.102	1.91±0.122	0.495±0.091	0.336±0.053	11.10±1.59	315.06
Descending Colon	M	1.40±0.175	1.85±0.183	0.406±0.076	0.285±0.052	10.41±1.86	339.19
	F	1.40±1.42	1.98±0.188	0.406±0.070	0.295±0.045	9.38±0.97	315.06

σ: $P_B D_B / 2t_B$, bursting circular stress

5. CONCLUSIONS

In summary, the in vivo G.I. rupture strength tests showed that:

- The physical dimensions and rupture pressure of each part of the large intestine do not appear to vary with the body weight of the rabbits, and there is little difference between male and female rabbits.
- The ascending colon has the highest bursting pressure because of its unique structure: closely spaced scalloped configuration and reinforcing side tissue.
- The rupture strength in terms of intestinal diameter and wall thickness decreases systematically from the caecum to the descending colon.

*Yamada, H., Strength of Biological Materials, edited by F. G. Evans, The Williams & Williams Co., Baltimore, 1970.

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